

1995-120457

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MODELS OF SYMBIOTIC STARS

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I. GENERAL INTRODUCTION

As it can be seen from Chapter 11 of this monograph, we need to explain many features of symbiotic stars. One of the most important is the coexistence of a cool spectral component that is apparently very similar to the spectrum of a cool giant, with at least one hot continuum, and emission lines from very different stages of ionization. The cool component dominates the infrared spectrum of S-type symbiotics; it tends to be veiled in this wavelength range by what appears to be excess emission in D-type symbiotics, this excess usually being attributed to circumstellar dust. The hot continuum (or continua) dominates the ultraviolet. X-rays have sometimes also been observed.

Another important feature of symbiotic stars that needs to be explained is the *variability*. Different forms occur, some variability being periodic. This type of variability can, in a few cases, strongly suggest the presence of eclipses of a binary system. One of the most characteristic forms of variability is that characterizing the active phases. This basic form of variation is traditionally associated in the optical with the veiling of the cool spectrum and the disappearance of high-ionization emission lines, the latter progressively appearing (in classical cases, re-appearing) later. Such spectral changes recall those of novae, but spectroscopic signatures of the high-ejection velocities observed for novae are not usually detected in symbiotic stars. However, the light curves of the "symbiotic nova" subclass recall those of novae. We may

also mention in this connection that radio observations (or, in a few cases, optical observations) of nebulae indicate *ejection* from symbiotic stars, with deviations from spherical symmetry.

In the following, we shall give a historical overview of the proposed models for symbiotic stars and make a critical analysis in the light of the observations discussed in Chapter 11. Then we describe the empirical approach to models and use the observational data to diagnose the physical conditions in the symbiotic stars. Finally, we compare the results of this empirical approach with existing models and discuss unresolved problems requiring new observational and theoretical work.

II. HISTORY AND OVERVIEW OF SIMPLE MODELS

Several types of model are conceivable, if one takes as a starting point the fact that the spectra are composite. For instance, it can be supposed that one has a single object with several regions whose physical properties are very different or that one has a binary. Following Friedjung (1982), we shall broadly classify simple models into the following categories:

- (a) Single-star models having a hot central object surrounded by a cool envelope.
- (b) Single-star models having a cool central object surrounded by a hot envelope.
- (c) Binary models.

It must be noted that single-star models without spherical symmetry are also possible and have sometimes been suggested.

The simplest sort of explanation is of type (c), and this was the one the first suggested. It was proposed by Berman (1932) for several stars, and by Hogg (1934) for Z And. Berman suggested the presence of an extremely faint O star that would be too faint to be seen, enclosed by a small nebular shell of high excitation. Binary motion and the proximity of the nebular shell were supposed to be possibly responsible for the observed variations. He thought that duplicity might be directly seen using a powerful instrument. Hogg (1934) proposed that Z And consisted of a normal M giant and a variable very hot dwarf that excited a nebular envelope, perhaps ejected in nova-like outbursts.

Kuiper (1941) suggested that stars such as Z And, VV Cep, T CrB, CI Cyg, AX Per, etc., might be examples of what he called ejection of type A in binaries. To use present day language, a giant fills its Roche lobe, and material is ejected near the inner Lagrangian point, tending to go into orbit around a compact companion. A binary model for BF Cyg, proposed by Aller (1954a) is illustrated in Figure 12-1.

However, it is generally not easy to find direct evidence of binarity for symbiotic stars, so various single-star models were proposed. Menzel (1946) suggested a hot central star with cool envelope model for different kinds of giant star. He proposed that the cool envelope of R Aqr lay only over the poles or only around the equator.

In a similar way Sobolev (1960) gave an explanation for cool stars with emission lines,

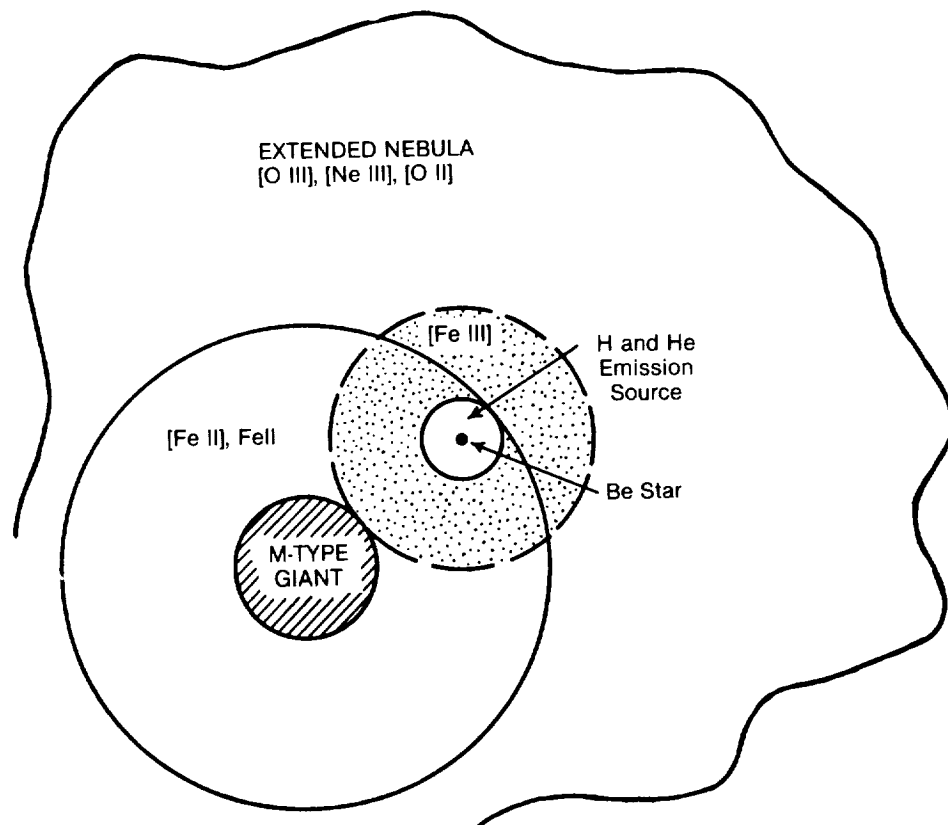


Figure 12-1. A binary model proposed for the symbiotic star BF Cyg (Aller, 1954a).

which symbiotic stars can be considered to resemble at certain times in certain wavelength ranges. According to Sobolev, such stars had a hot nucleus surrounded by an envelope with a significant optical thickness in subordinate continua like the Balmer continuum of hydrogen, giving rise to a cool absorption line spectrum.

The Sun and similar stars can from a certain point of view, also be thought of as "symbiotic". The same star has a relatively cool spectrum in the optical and high-ionization emission lines in the far-UV. This is explained in the solar case by the presence of a hot chromosphere, transition region and corona above a fairly cool photosphere, and quite a number of attempts have been made to explain symbiotic stars with this kind of model. Aller (1954b) suggested that such a picture with heating produced by the dissipation of shock waves could be an alternative to a binary model. Gauzit (1955 a,b) tried to explain observations of the symbiotic star AX Per using this kind of model. His studies of relative line-intensity variations appeared to him hard to explain using a binary model. However, it may be noted that stratification effects can be complex, particularly in a binary system.

Wood (1974) made theoretical calculations concerning a model with a cool photosphere and hot chromosphere. An asymptotic-branch giant star had pulsations and relaxation oscillations; noise from shocks heated the chromosphere.

A new impulse was given to binary models by the work of Boyarchuk (1966, 1967a, 1968, 1969a, 1969b, 1975, 1976b). Energy distributions of a number of symbiotics were studied and interpreted as due to three components: a cool giant, a small hot star with a temperature near 10^5 K, and an ionized nebula. The hot star was assumed to radiate as a blackbody, while the nebula was supposed to be optically thick to photons with wavelengths less than 912 Å, and optically thin at longer wavelengths. Optical range energy distributions were explained for a number of stars, including AG Peg

and Z And. The variations of Z And were interpreted by changes in the temperature of the hot star at almost constant bolometric magnitude.

At present, workers in the field of symbiotic stars with few exceptions consider that almost all symbiotics, if not all, are interacting binaries. The question now is since about 1980, to find out *which processes dominate in which stars*. One major reason for this shift in attitude is the impact of ultraviolet observations with the IUE satellite, which cannot be easily explained in the framework of single star models. In the following we shall give a more detailed description of models and how they can be tested.

III. SINGLE STAR MODELS

III.A. HOT STAR WITH COOL ENVELOPE

We shall consider two forms of such a model. The first form to which the already mentioned historical models belong has dense envelopes, with a nonnegligible optical thickness in the continuum at most wavelengths. Without detailed calculations, it is possible to make simple predictions for the behavior of symbiotic stars that would be described by the first form of the model, these appearing, in general, to be contradicted by the observations.

Firstly, as we have already seen in Chapter 11, the cool spectral component very much resembles that of a cool star without signs of abnormalities. We shall come back to this point in Section III.B. In addition, a cool envelope might be expected to consist of cool regions of the wind of the late-type central star. As will be seen, the source of the hot continuum needs to come from a rather small object, which would be a subdwarf in the present case. A wind velocity on the order of the stellar escape velocity (around $1-3 \cdot 10^3$ km s⁻¹) might then be expected. Neither emission lines with a corresponding Doppler width nor absorption lines with a corresponding blue shift are usually observed, AG Peg perhaps being an exception. In addition, both line and continuum absorption of the hot continuum by the cool envelope

might be expected unless there were large deviations from spherical symmetry. No indications of a modification of emission line fluxes in the optical because of overlying absorption are seen as pointed out by Boyarchuk (1969b). Similarly, as discussed in Section 11.VIII.C, no clear sign of hot continuum absorption by non-interstellar excited neutral absorption lines has been reported in high dispersion UV observations. Moreover, when low excitation lines are seen in the near UV, they do not appear to be associated with the spectrum resembling that of a cool star. For instance, Faraggiana and Hack (1971) found that the M6III-type absorption spectrum of CH Cyg was veiled by the blue continuum present in 1967. Johnson (1982), however, claimed that continuum absorption by amorphous silicate smoke might occur in the UV of R Aqr. Nevertheless, as pointed out by Johnson, even this could be explained by a binary model with absorption of hot continuum radiation by the cool star's wind.

Absorption of the hot continuum might be less important if there were deviations from spherical symmetry, such as in the model suggested by Menzel (1969), further extending his 1946 proposal, with a cool ring formed by a magnetic field around the hot star. However, as previously seen, the cool component observed in symbiotic stars appears very normal. Also, no magnetic fields were detected by Slovak (1978) for symbiotic stars.

Another argument was given by Boyarchuk (1982). "If we propose that a symbiotic star is a hot star with a hot nebula, and that TiO-bands and other absorption features are formed in other parts of this nebula, we should note that in the spectra of many symbiotic stars we observe the absorption line of CaI 4227 Å. This line has very extended 'wings' which is normal for a cool star spectrum. But, if we calculate the column density which is needed to produce such wings in a nebula, and multiply by the surface of the nebula which is huge, then we will obtain the mass of the absorption envelope that is equal to several solar masses. It is difficult to understand how such envelope could exist".

The second form of the hot central star with cool envelope model is to suppose that one has an object rather like a compact planetary nebula. This sort of explanation can be attempted for D-type symbiotics for which indications of the presence of the cool spectral component are less clear in the visual. Nussbaumer and Schild (1981) made a proposal of this kind for V1016 Cyg. They calculate the emission line fluxes with their model; emission came from a shell with a mass of ionized hydrogen of $3 \times 10^{-4} M_{\odot}$ surrounding a hot star with an effective temperature of 1.6×10^5 K and a radius of $0.06 R_{\odot}$. Other single star models for this object exist, such as those discussed by Baratta et al. (1974) and Ahern et al. (1977).

The objection connected with the absence of spectroscopic signatures of a high-velocity wind have less importance for the last kind of model. This is because a low-velocity envelope, in principle, could have been ejected from a previously existing red giant with a much lower escape velocity, this giant then having become a subdwarf (see Figure 12-2). Indeed according to the mechanism of Kwok et al. (1978) a planetary nebula might be formed as a result of the collision of the wind of a subdwarf and that of the pre-existing red giant. However the evidence for the existence of a cool star spectral component even for D-type symbiotic stars seems to contradict planetary nebula types of model.

III.B. COOL STAR WITH HOT ENVELOPE

As for the previously considered single-star models, rather simple considerations lead to major problems for cool star with hot envelope models. It is hard for the present models to produce the strong observed hot continua already studied by Boyarchuk (1967a, 1968, 1969a) in the optical, and in more recent years, well-studied in the satellite ultraviolet. The energy radiated in different forms will be discussed later, but we can anticipate by stating that the energy radiated by the hot continuum and the emission lines is of the same order as that due to the cool spectral component. Let us

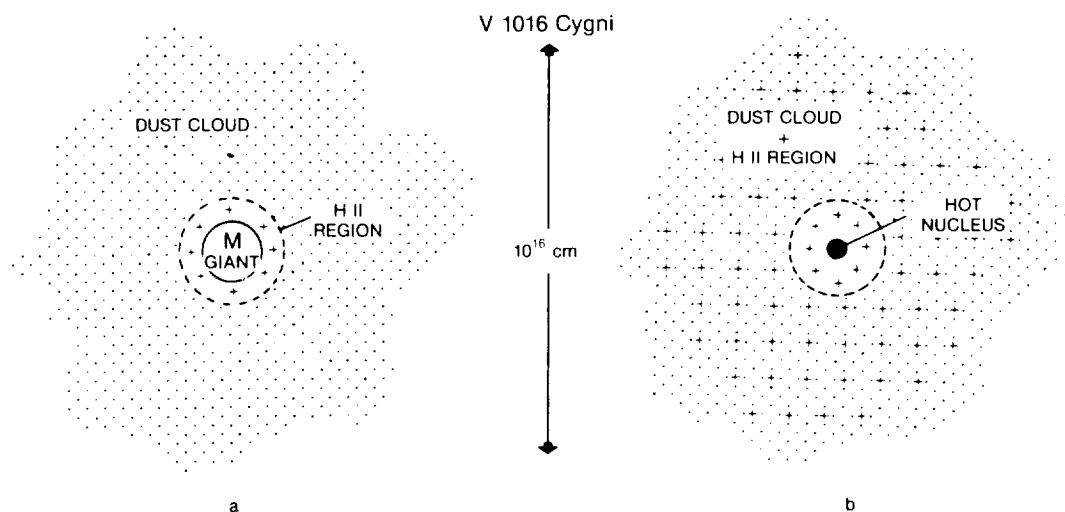


Figure 12-2. Single-star model proposed for the symbiotic nova V1016 Cyg: a Mira-type variable red giant loses its outer envelope and becomes a hot subdwarf, whose radiation ionizes the low-velocity circumstellar nebula produced by the red giant wind during the precoutburst phase (Baratta et al., 1974).

also mention a calculation performed by Altamore et al. (1981) for Z And; the regions producing the emission lines of highly ionized atoms seen in the UV could not produce the strong UV continuum observed in Z And. This result does not appear very easy to change, even with other assumptions for the calculations.

One can try to avoid some of the problems associated with the production of the hot continuum, if it is assumed to be produced by optically thick spots of the cool star's photosphere resembling solar faculae. Wdowiak (1977) suggested a model of this type for CH Cyg involving magnetic heating following a prediction of kilogauss surface magnetic fields, while Oliverson et al. (1982) suggested the presence of a large spot with associated magnetic activity to explain the phenomena of AG Dra. The lack of detection of coherent magnetic fields for CH Cyg, AG Peg and, EG And by Slovak (1978), however, poses a special problem for this form of model.

Other types of arguments against models of cool stars surrounded by coronae have been given by Kenyon (1986, p.13). He based his reasoning on results obtained by Hartman et al. (1981, 1982) concerning more "normal" late type stars. In the latter, the flux of the HeII

1640 Å line is correlated with X-ray emission observed using the Einstein satellite, as expected if a substantial part of the double photoionization of helium is due to X-ray radiation from a hot corona with temperatures above 10^6 K. Kenyon points out that T CrB and V1017 Sgr have X-ray emission without HeII 1640 Å, while R Aqr and AG Dra show X-ray emission that is one to two orders of magnitude less than that predicted from HeII. The two former stars are usually considered rather to be recurrent novae, and perhaps, they may be different from most of the stars considered in this chapter, while the results from the two latter stars indicate either a different mechanism for photoionizing helium (e.g., the photosphere of a hot star) or a relatively cool corona. Kenyon (1986, p.13) also argues from the NV 1240 Å/CIV 1550 Å flux ratio observed for "normal stars"; this ratio can be much lower in symbiotic star spectra. One may conclude, perhaps, in the light of the arguments given by Kenyon, that any symbiotic star corona, if present, would have to be rather unusual.

If we consider single-star models in general, we also see that the explanation of the variations is not clear. How can one produce what appear to be eclipses, while though it might not be impossible to explain active phases, explanations of them appear rather vague? In any

case, in view of what has been said, single-star models seem difficult to support, unless rather artificial assumptions are made. Therefore, we shall not pay very much more attention to them in the following discussion.

IV. BINARY MODELS

Binarity is very common among stars, and interaction between components can lead to many effects when these components are close. As we shall see, binary models have a strong predictive power. In any case, it is immediately obvious that composite spectra and eclipses are straightforwardly explained in the framework of such models. The main signature of close binarity, radial velocity variations, has been discussed in Section 11.X.D. Evidence for the presence of such variations has been rapidly improving.

Instead of considering particular models, it is more useful to consider the different processes that can occur in binaries. Several processes could be responsible for the phenomena in symbiotic stars: the question will be which process is dominant. In addition, the physics of these processes is often still badly understood, and different possibly conflicting phenomena need to be mentioned.

In all the following discussion, we shall suppose, as discussed in Section 11.X.B, that the cool spectral component is really produced by a cool giant star. The different processes and phenomena lead to conflicting interpretations of the nature of the hot component and concern the interactions between the components. We shall now consider the different processes and possible phenomena.

IV.A. HOT COMPONENT AS A SUBDWARF OR A REJUVENATED WHITE DWARF

The simplest interpretation is that the hot continuum comes directly from a hot star similar to the nucleus of a planetary nebula. In this case, we can predict the form of the continuum. In addition, if the emission line fluxes and

radio emission come from an HII region, we can, in principle, obtain information about unobservable wavelength ranges of the continuum that photoionizes the HII region. In this way, analysis of the observations leads to the deduction of the characteristics of the hot star. This type of analysis, to be described later, was performed by Kenyon and Webbink (1984).

If such an interpretation is accepted, active phases must be linked to changes in the properties of the hot component. In fact, a fair amount of theoretical work has been done, supposing that the hot component is an accreting white dwarf undergoing thermonuclear events or even continuous shell burning. The accreted material then comes from the stellar companion by processes that will be considered later. According to Iben (1982), the condition for steady hydrogen burning is

$$\dot{M} \gtrsim 1.32 \times 10^{-7} M_{\text{wd}}^{3.57} M_{\odot} \text{ yr}^{-1},$$

where \dot{M} is the mass accretion rate in solar masses per year and M_{wd} , the white dwarf mass in solar masses. For an \dot{M} above a slightly larger limit, the envelope of the accreting star expands so it resembles a giant, while for smaller rates, recurrent outbursts occur.

The different forms of possible behavior of an accreting white dwarf were studied in detail by Fujimoto (1982a, b), and are summarized in Figure 12-3 taken from the second of these papers.

In general, two types of stable configuration of accreting white dwarf exist, according to Fujimoto. In one, nuclear shell burning compensates for energy losses; in the other, gravitational energy release balances the radiative energy loss. Steady burning occurs in the former configuration, which has a lower limit to the mass of the hydrogen-rich envelope. For lower accretion rates, transitions occur between these two configurations, which are not stable. Starting from the second configuration, accretion leads to an increase in the mass of the hydrogen-rich envelope. A "hydrogen shell flash" then occurs, associated with a transition

to the other configuration. If energy losses are larger than thermonuclear energy generation, this new state does not last, and the white dwarf returns to its initial state. The cycle is then repeated.

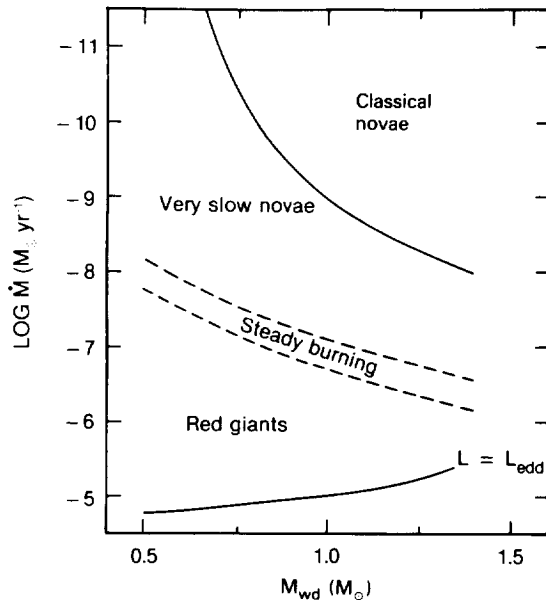


Figure 12-3. Behavior of accreting white dwarfs in a graph of white dwarf mass against the accretion rate, according to Fujimoto (1982b).

Examining in more detail Figure 12-3, one sees first the region at the bottom of the figure; that is where the envelope of the white dwarf expands, so as to make it like a giant. The star will then fill its Roche lobe; if the companion also fills its Roche lobe a sort of contact binary will be formed; otherwise, the system will be semi-detached with mass transfer *from* the expanded white dwarf *to* its companion. For lower accretion rates, steady state burning occurs, and the expanded white dwarf will be a strong source in the extreme UV. Even lower accretion rates are associated with recurrent events, their nature depending on the extent to which the white dwarf expands. It expands during hydrogen burning to less than a solar radius for higher accretion rates, and to larger radii for lower rates. Finally, for very low accretion rates, the white dwarf envelope expands at high velocity during a shell flash, and a nova explosion occurs. However, the limits of

this theory should be noted; in particular, a simple interpretation of observations of classical novae in quiescence suggests higher accretion rates than would be possible, according to the calculations of Fujimoto.

Fujimoto (1982b) also calculates time scales. During a shell flash, the duration of burning is

$$\tau = \Delta M_i / (\dot{M}_{\text{ex}} - \dot{M}),$$

where M is the mass of the accreted envelope, \dot{M}_{ex} the minimum mass accretion rate for steady burning, and \dot{M} the actual rate. Hence, for ΔM_i equal at ignition to $10^{-6} M_{\odot}$ and a value of $(\dot{M}_{\text{ex}} - \dot{M})$ of $3 \times 10^{-7} M_{\odot} \text{ yr}^{-1}$, τ is 3 years.

Explanations of symbiotic stars using such models were proposed by Tutukov and Yungelson (1976), Paczynski and Zytzkow (1978), Paczynski and Rudak (1980), and by Kenyon and Truran (1983). Paczynski and Rudak divided symbiotic stars into two classes. In *type I* symbiotic stars, the luminosity was produced in a stable burning hydrogen shell; small variations of accretion rate led to changes of radius and effective temperature of the expanding white dwarf at constant bolometric magnitude. Thus, an active phase of this type of symbiotic star was associated with a small increase of the accretion rate; the effective temperature dropped while the radius increased, causing an increase of the visual brightness over a time scale of the order of $\Delta M_i / \dot{M}_{\text{ex}}$ (using our previous notation), estimated by Paczynski and Rudak as of the order of 2.5 years. *Type II* symbiotic stars, according to the explanation of Paczynski and Rudak, have an accretion rate below \dot{M}_{ex} , and therefore, are undergoing recurring shell flashes. This explanation was used for symbiotic novae.

Shell flashes were also discussed by Kenyon and Truran (1983) and by Kenyon (1986) to explain the symbiotic novae phenomenon. The rise to visual maximum is characterized by two phases illustrated in Figure 12-4.

A rapid increase in bolometric luminosity at

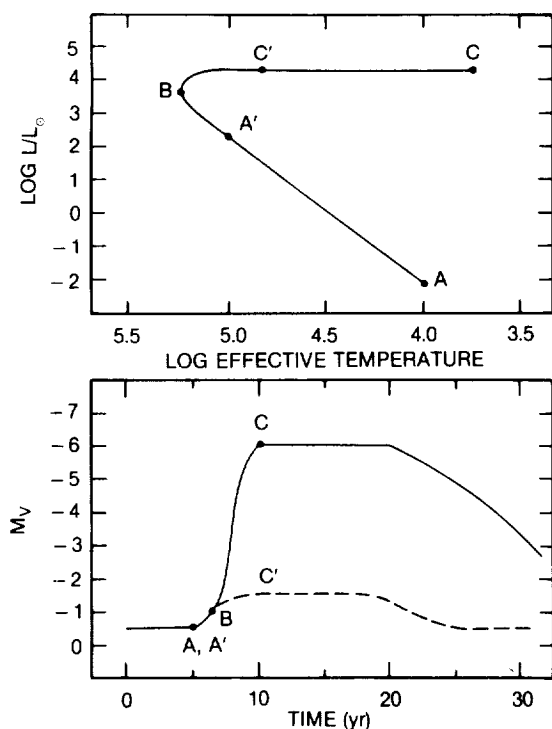


Figure 12-4. Time evolution of a white dwarf undergoing a thermonuclear flash. (a) The path in the H-R diagram. (b) The visual light curve (Kenyon 1986): A C, strong flash; A C', weaker flash.

almost constant radius (A to A' in Figure 12-4) is followed by a phase at nearly constant bolometric luminosity (C to C' in the figure). In the first phase, the visual brightness is almost constant while the effective temperature of the star increases, so being able to strongly ionize any surrounding nebula. In the later phase, however, the temperature drops and the visual brightness rises (see Figure 12-4b). Weaker flashes lead to shorter tracks in the H-R diagram (for instance to C' in the figures). Kenyon and Truran (1983) divided symbiotic novae into two classes. RR Tel, RT Ser, and perhaps AG Peg had strong flashes, showing like classical novae B-F supergiant spectra at maximum, characteristic of not very high temperatures. V1016 Cyg, V1329 Cyg, and HM Sge were considered to be examples of weak shell flashes; they did not evolve into F supergiants and had planetary nebula-type spectra even at maximum. We shall discuss this point again in Chapter 13, Section IV.C.

We can conclude this section by stating that

binary models containing an expanded white dwarf component appear promising in certain respects at least. Future work will show whether they really represent the observations well.

IV.B. ACCRETION PROCESSES

Accretion has already been invoked in the discussion about expanded white dwarfs. It can play a dominant role in other ways, and we shall now discuss them. Two simple sorts of accretion are conceivable, (1) via a disk following Roche lobe overflow, and (2) from the wind of the companion star.

The former type of accretion has already been extensively discussed for dwarf novae, novae in quiescence, and nova-like cataclysmic variables in this volume. In a classical case, material flows from the inner Lagrangian point in a stream that strikes the accretion disk at a bright spot. Angular momentum is lost in the disk and a boundary layer is formed between the disk and the mass gaining star. As in the previous situation where the hot continuum came directly from a star, one can calculate a theoretical energy distribution for observable and also unobservable spectral regions able to photoionize various atoms. The methods of calculating the energy distribution are the same as for dwarf novae, novae in quiescence and nova-like cataclysmic variables.

Kenyon and Webbink (1984) have calculated theoretical energy distributions for symbiotic stars, supposing that the hot component was due to accretion. They assumed that radiation was emitted by a disk locally radiating as a blackbody (that is, by a disk consisting of a sum of blackbodies at different temperatures) and a boundary layer radiating as a blackbody at one temperature. The inclination of the disk and occultation of part of the boundary layer were taken into account. Kenyon and Webbink considered accretion both onto a white dwarf, and onto a main sequence star, and found no example of the former case when comparing theory and observations. For stars whose continuum energy distribution suggested a main

sequence accretor model, difficulties were encountered in explaining emission line intensities as due to photoionization. This type of approach will be considered in more detail below, but it is already clear that it needs to be refined in future work.

In cataclysmic binaries, emission line formation in or near a disk leads to double peaked profiles for large inclinations (Smak, 1981). A bright spot, if present, would lead to an S wave profile as for cataclysmic binaries (see Section 2.III.B.1.e), and variations in the ratio of the violet to the red peak over the orbital cycle.

Eclipses of an accretion disk should also lead to characteristic time variations of the continuum and the emission line profiles, as seen for cataclysmic binaries. This is because an accretion disk does not have the same brightness distribution at a given wavelength as a star, while different parts having different rotational velocities contribute to different parts of line profiles, eclipsed at different times. (The theory of this is described in Section 4.III of this Monograph).

When accretion occurs from a wind, disk formation is difficult, because only a small amount of angular momentum should be accreted. The three-dimensional theory has been treated by Livio et al. (1986a,b). The second of these papers describes the results of calculations in three dimensions, taking account of pressure. Conditions necessary for the formation of a disk were obtained in that paper. Enough angular momentum must be accreted for material to be able to rotate at a Keplerian velocity at the radius of the accretor at least. Livio et al. (1986b) give a condition for the formation of a disk in their equation (21):

$$V_{\text{rel}} \leq 3.7 \times 10^6 (\xi/0.2)^{1/4} (M_{\text{wd}}/0.6)^{3/8} (P/10\text{y})^{1/4} \\ (R_{\text{wd}}/4.5 \times 10^8 \text{ cm})^{-1/8} \quad (12.1)$$

Here V_{rel} is the relative velocity of the wind and the accreting object, $\xi = l/l_{\text{BH}}$ is the ratio of the accreted angular momentum to that deposited at the radius of accretion, according to the

classical theory of Bondi and Hoyle (1944), M_{wd} the mass of the accreting star (taken to be a white dwarf by Livio et al.), R_{wd} the radius of the accreting star, and P the orbital period. The calculations of Livio et al. (their Table 1) give values of ξ ranging from 0.10 to 0.23, depending on the assumed Mach number and ratio of specific heats. For a symbiotic star having a period of 2 years, ξ equal to 0.15, a white dwarf accretor with a mass of $1.0 M_{\odot}$ and a radius of $9.5 \times 10^8 \text{ cm}$, the condition is $V_{\text{rel}} < 28 \text{ km s}^{-1}$. For a main sequence accretor with a radius of $6 \times 10^{10} \text{ cm}$, this condition becomes $V_{\text{rel}} < 17 \text{ km s}^{-1}$. Wind velocities of red giants can be expected to be very low; if the orbital part of V_{rel} is near 20 km s^{-1} , formation of a disk around a white dwarf may be possible following wind accretion. Livio (1988) found that a disk could be formed by wind accretion round a white dwarf accretor of the symbiotic star AG Dra.

There are, however, many uncertainties in the theory of disk formation from winds. For instance, the two dimensional calculations of Matsuda et al. (1987) found nonsteady behavior with the accreted angular momentum being able to change sign. More work remains to be done, before one can be sure when disks can be formed by accretion from a wind.

Accretion processes can also be invoked to explain the active phases of symbiotic stars. The models are fairly similar to those for the outbursts of dwarf novae, described in Chapter 3. As for the latter, one can conceive both of instabilities of the secondary leading to times when the mass transfer rate is enhanced, and of instabilities of the accretion disk, if one is present.

In addition to the dwarf nova type of instability proposed by Bath (1975, 1977) for a cool component of such a binary, another type of instability was suggested by Kenyon (1986), associated with recurrent helium shell flashes. A cool giant in a double shell phase of evolution is modeled with secular combustions in two shells; an outer shell burning hydrogen to helium and an inner shell burning helium. The latter is unstable because of the presence of a

convective envelope above it, preventing expansion associated with an increase of thermal energy. Such an increase leads to a sudden increase of energy generation of the helium shell and a large expansion, which temporarily extinguishes the hydrogen binary shell. Such events should not have much effect on the surface properties of a single red giant, but according to Kenyon (1986), the small predicted increase in photospheric radius could power a mass transfer instability. The phenomenon is predicted to be periodic with a period P in years given by

$$\log P = 3.05 - 4.5 (M_{\text{core}} - 1.0M_{\odot}) \quad (12.2)$$

Kenyon fitted this expression to observed activity of R Aqr; a 44-year period would correspond to a core mass of $1.3 M_{\odot}$ and a bolometric magnitude of -7 . This was thought tolerably close to the observed one of symbiotic stars, considering both the theoretical uncertainties and the uncertainty in the distance of the star.

It may be noted that periodic mass transfer events could also occur at periastron, if the orbits were eccentric. Determinations of the eccentricity of orbits by Garcia and Kenyon (1988) suggest that in some, but not all, cases, the orbits are fairly circular (see Section 11.X.D), rendering such a mechanism fairly unlikely for those stars at least.

Disk instability calculations were made by Duschl (1983,1986a,b). In the latter of these papers, calculations were made in cases of accretion by a one-solar mass main sequence star. The limit cycle instability model led to heating and cooling fronts crossing the disk; reflection of a front of one type led to propagation of a front of the opposite type. Conditions for this type of model to work for symbiotic stars indicated breakdown of the model as follows (Duschl 1986b):

- A: The description breaks down, as the disks are no longer geometrically thin.
- B: The disks are too large, so that the outbursts are too rare to be consistent with

the observations.

- C: The outbursts occur too rarely, as the mass transfer rate is too low.
- D: No outbursts occur at all, as the unstable branch does not appear within the disk; i.e., the disk can be everywhere stationary on the upper branch.
- E: Maximum brightness is too small to be consistent with observations.

The regions in which disk instabilities are possible are shown in a diagram of the accretion rate and the disk radius, according to Duschl, in Figure 12-5.

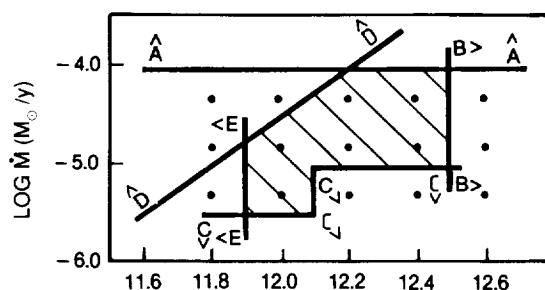


Figure 12-5. Location of possible models for symbiotic stars (shaded area), according to Duschl (1986b). The restrictions AA to EE are those described in the text. Abscissae are log of the outer radius of the disk r_0 , and ordinates log of the mass transfer rate.

In situations where accretion from a wind occurs, the accretion rate varies inversely as the fourth power of the relative (wind + orbital) velocity of the accretor and the wind. A decrease in the wind velocity would, therefore, cause an increase in the accretion luminosity. However, it is very difficult for a high enough luminosity to be produced for a main sequence accretor, because the calculations of Kenyon and Webbink (1984) indicate accretion rates of $\sim 10^{-5} M_{\odot} \text{ yr}^{-1}$ in such cases, and the mass-loss rate of a cool giant wind would have to be even greater.

It is hard to assess the relevance of models involving accretion rate changes. In general, simple models would predict that activity is associated with temperature increases of the disk and, hence, a flux increase at all wavelengths. However, the behavior of the boundary layer in particular needs also to be taken

into account. The theories of disks plus boundary layers are sufficiently uncertain that it is not sure whether accretion events can be ruled out when observations clearly indicate that the hot source cools during an outburst. Therefore, it is premature to make a judgement of this type of theory.

IV. C. WINDS FROM BOTH COMPONENTS

The strong wind expected from the cool giant component of a symbiotic binary should have important effects. Emission lines and, in certain conditions, absorption lines can be produced; indeed, it can be what is sometimes called the "nebula".

The winds of normal cool giants have rather low velocities of the order of 10^1 km s^{-1} , and can be expected to give rise to rather narrow emission lines. Radiative transfer in an expanding medium can be expected to produce radial velocity differences between the centers of optically very thick resonance and optically thin lines. This is because a multiply scattered photon inside the profile of an optically thick line formed in such a medium will be somewhat redshifted by each scattering, producing a net redshift of the emission line. In addition, if the continuous spectrum is not too weak, this type of line will also have a blueshifted P Cygni absorption component eating into the blue wing of the emission line, and so increasing the mean redshift of the observed line emission. Such a difference between the radial velocities of high-ionization resonance lines and semiforbidden lines has been observed in the ultraviolet spectra of a number of symbiotic stars (Friedjung et al., 1983).

Photoionization can be expected to be due to the hot companion, which is not at the center of

the cool component's wind. Ionization models must take this lack of spherical symmetry into account. The consequences of this were first calculated for the interpretation of radio observations by Seaquist et al. (1984) and by Taylor and Seaquist (1984). In these papers, the geometry of the ionization boundary is calculated as a function of $f(u, \theta)$ with u a radial distance centered on the hot star and normalized to the binary separation, and θ the angle between a line joining a point to the central star and that joining the two stars. Then $f(u, \theta)$ was set equal to X at the boundary, where

$$X = 4 \pi \mu^2 m_H^2 / \alpha a L_{ph} (\dot{M}/V)^2 \quad (12.3)$$

Here \dot{M} is the cool component mass loss rate, V is the wind velocity assumed constant, a is the distance between the two stars, L_{ph} is the flux of hydrogen ionizing photons per second emitted by the hot component, α is the recombination coefficient, m_H is the mass of a hydrogen atom, and μ the molecular weight. Finally, the expressions given by equations (12.4) were used for $f(u, \theta)$.

The relative orbital motion of the stars is neglected, and velocities are supposed low enough that local ionization is in equilibrium. The results of calculations of the form of the ionized region and the resulting radio spectrum are shown in Figure 12-6 from Seaquist et al. (1984).

This type of model has been extended by Nussbaumer and Schmutz (1983), Nussbaumer et al. (1986), and by Nussbaumer and Vogel (1987). The most detailed calculations are in the last of these papers. The wind is supposed to be accelerated with a velocity law of the form:

$$V_r = (1-R/r)^{\beta} V_{\infty}$$

Where r is the distance from the star's cen-

$$f(u, \theta) = \begin{cases} \frac{1}{3(1-u)^3} - \frac{u}{(1-u)^3} - \frac{1}{3}; & \theta=0 \\ \frac{(2 \cos^2 \theta - 1)u - \cos \theta}{2 \sin^2 \theta (u - \cos \theta)^2} + \frac{1}{2 \sin^2 \theta} \left[\tan^{-1} \left(\frac{u - \cos \theta}{\sin \theta} \right) + \tan^{-1} (\cot \theta) \right] + \frac{\cos \theta}{2 \sin^2 \theta}; & \theta \neq 0, \pi \\ \frac{1}{3} - \frac{u}{(1+u)^3} - \frac{1}{3(1+u)^3}; & \theta=\pi. \end{cases} \quad (12.4)$$

ter and R, the radius for the origin of the wind, while the constant β was assumed equal to 1. Emission line profiles were calculated assuming the lines optically thin. Nussbaumer and

Vogel considered the non-validity of this assumption to be responsible for the calculated HeII 1640 Å flux of V1329 Cyg, being too strong at minimum brightness.

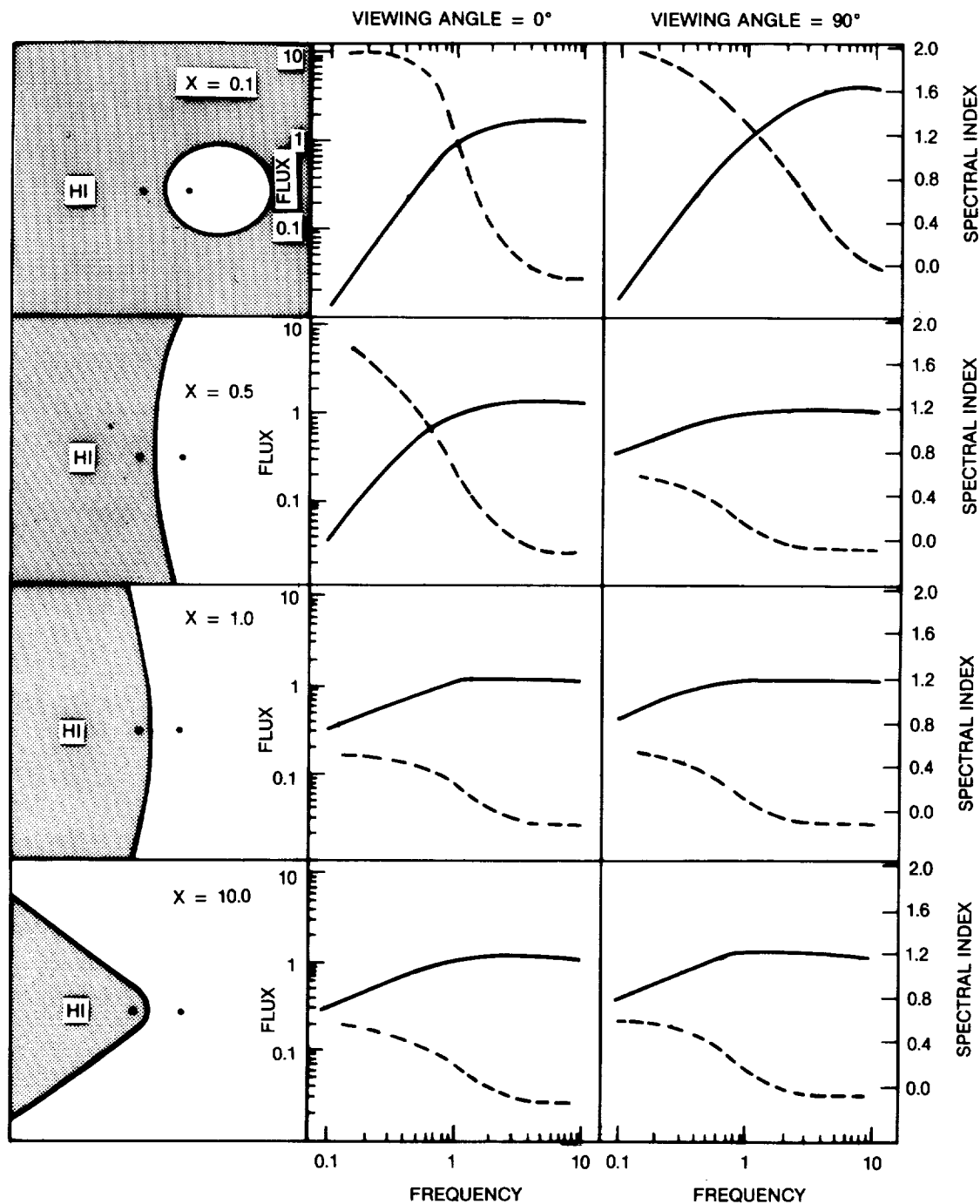


Figure 12-6. Left: the shape of the ionization front for various values of the parameter X (eq. 12.3). The position of the red giant (left) and hot star (right) is also shown. Centre and right: the radio spectra for two viewing angles, along the axis joining the two stars ($\alpha=0^\circ$), and at right angles ($\alpha=90^\circ$). Solid lines are flux densities, while dashed lines are the spectral indices.

Nussbaumer and Vogel (1987) also propose an explanation for what happens when a symbiotic star becomes active. According to them, the mass-loss rate from the cool star then increases, causing a change in the geometry of the ionized regions and, hence, a variation of emission line and continuum radiation due to recombinations. Clearly, such a mechanism cannot work in a situation where the initially present hot continuum cools or disappears.

The compact component's wind needs also to be taken into consideration. This could either be from the stellar companion or from an accretion disk if one is present. The velocity can be expected to be much higher than that of the wind of the cool giant and could produce wide emission components and wide P Cygni absorption components with a large blue shift, as indeed is seen for cataclysmic variables. There is also a possibility of collimation of a wind from a disk, and so a bipolar flow can be formed. For instance, Kenyon (1987) has proposed that such a wind could be driven by Alfvén waves and have a much larger velocity perpendicular to the disk than in other directions.

If two winds are present, collisions can be expected to occur between them. A number of papers have been written based on such models (Kwok et al, 1984; Wallerstein et al., 1984; Willson et al., 1984; Kwok and Leahy, 1984; Girard and Willson, 1987; and Kwok, 1988). The model is applied to symbiotic novae, for which the compact component is supposed to produce a high-velocity wind during the outburst, while the physical model has been derived in most detail by Girard and Willson (1987).

The situation is shown in Figure 12-7. Material accumulates on the boundary where the winds meet, and the nebular shell produced will be deformed as can be seen in the figure. Different regions of this shell will have different ionizations and so emit in different emission lines, which will not, therefore, necessarily have the same profile. The situation in the immediate vicinity of the binary is shown in the

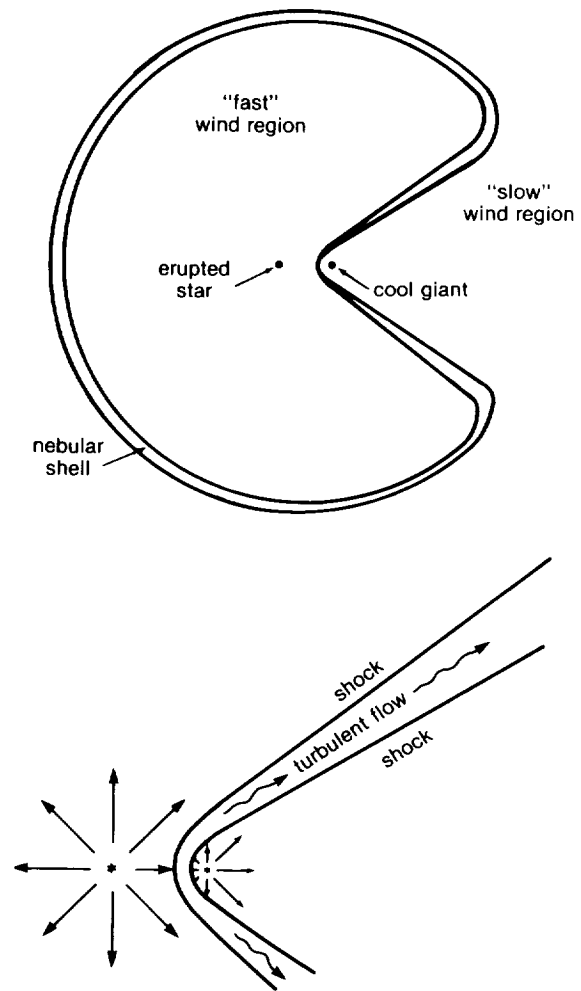


Figure 12-7. Colliding wind geometry, according to the model of Girard and Willson (1987).

lower part of the figure. A steady state configuration is reached there. This steady state was studied by Girard and Willson (1987), who first ignored the orbital motion of the binary and assumed the wind interaction region thin. Equations were derived based on mass and momentum conservation. The authors found that the shape of the shell only depended on the product $m.w$, where m is the ratio of the mass loss rates and w the ratio of the wind velocities. The steady state solutions indicate that the wind interaction occurred on the surfaces of truncated cones. The forms of these for different values of $m.w$ are shown in Figure 12-8.

Girard and Willson then calculated a dynamical shell model including orbital motion,

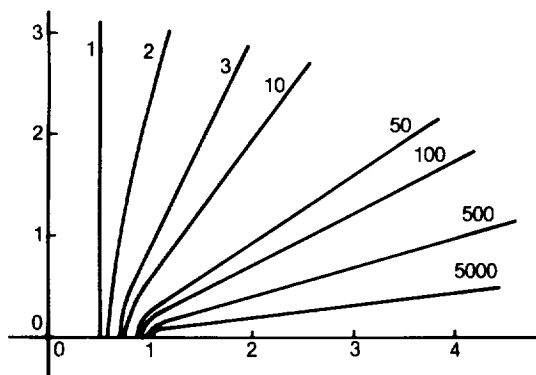


Figure 12-8. Steady state colliding wind solutions from Girard and Willson (1987). The star with the high velocity wind is at the origin of the coordinate system, while its companion is one unit away on the abscissae. The curves represent the sections of the interaction surfaces which have the form of truncated cones. Each curve is labelled with a value of $m.w$.

and assuming a sudden turn on of the high-velocity wind. The orbits were circular, and the stars of equal mass. The results of calculations for a stellar separation of 20 a.u., an orbital period of 60 years, wind velocities of 500 and 20 km s^{-1} and a high-velocity to low-velocity mass-loss rate ratio m of 2 are shown in Figure 12-9.

Certain forms might even mimic bipolar flows to some extent. The authors also speculated on the possibility of higher velocities of material in the hot shocked region near the apex of a cone than in other parts of this cone.

Kwok and Leahy (1984) calculated properties of X-ray emission from colliding winds. The emission is deduced to be from thermal bremsstrahlung of plasma at 10^7K characteristic of colliding winds. Girard and Willson (1987) also discussed X-ray emission; they were unable, however, to make a detailed prediction, as it was not clear what proportion of the available energy flux was radiated. In general, colliding wind models seem to need more physics.

IV.D. ENHANCED SOLAR-TYPE ACTIVITY OF THE COOL STELLAR COMPONENT

Another possibility is that the symbiotic phenomenon is due to increased solar-type

activity of the cool stellar component (Altamore et al., 1981; Friedjung et al., 1983; Friedjung, 1988). This could be associated with a higher rotational velocity than for normal cool giants because of tidal locking of the rotational and orbital periods. A region similar to the solar transition region might then produce the high-ionization emission lines observed, while small variations in the wind from the cool giant could cause large changes in the accretion rate to the compact component, and, hence, in the nature of any accretion disk. The model was proposed because early IUE observations of Z And suggested that the hot continuum was not hot enough to produce the highest ionization lines in photoionized regions, while some lines, at least, were formed in a region where high-temperature radiation was diluted, a region that is far from that where the hot continuum was formed. In addition, a certain form of reasoning suggested that this region was thin. The fact that high-ionization resonance lines of CI Cyg, unlike other lines of this star were little or not eclipsed also seemed to support the model. However, it now appears that enough high-energy radiation is generally present for photoionization. Mikolajewska (1986) showed that the high-ionization emission lines of CI Cyg had radial velocity variations, probably in phase with those of the compact component, and first results on the widths of absorption lines of the cool component of CI Cyg (Bensammar et al., 1988), suggest that the rotation of CI Cyg may not be tidally locked to its orbital period. The model may also have other problems. However, even if effects of increased activity of the cool giant are less important than originally proposed, the possibility of their presence should not be forgotten in future interpretations.

IV.E. CONCLUSIONS ABOUT THE MODELS

It appears that, in principle, it should be possible to learn a lot if one assumes the presence of accretion in interactive binaries either from Roche lobe overflow or from a wind. Such processes need not be steady; not only can the

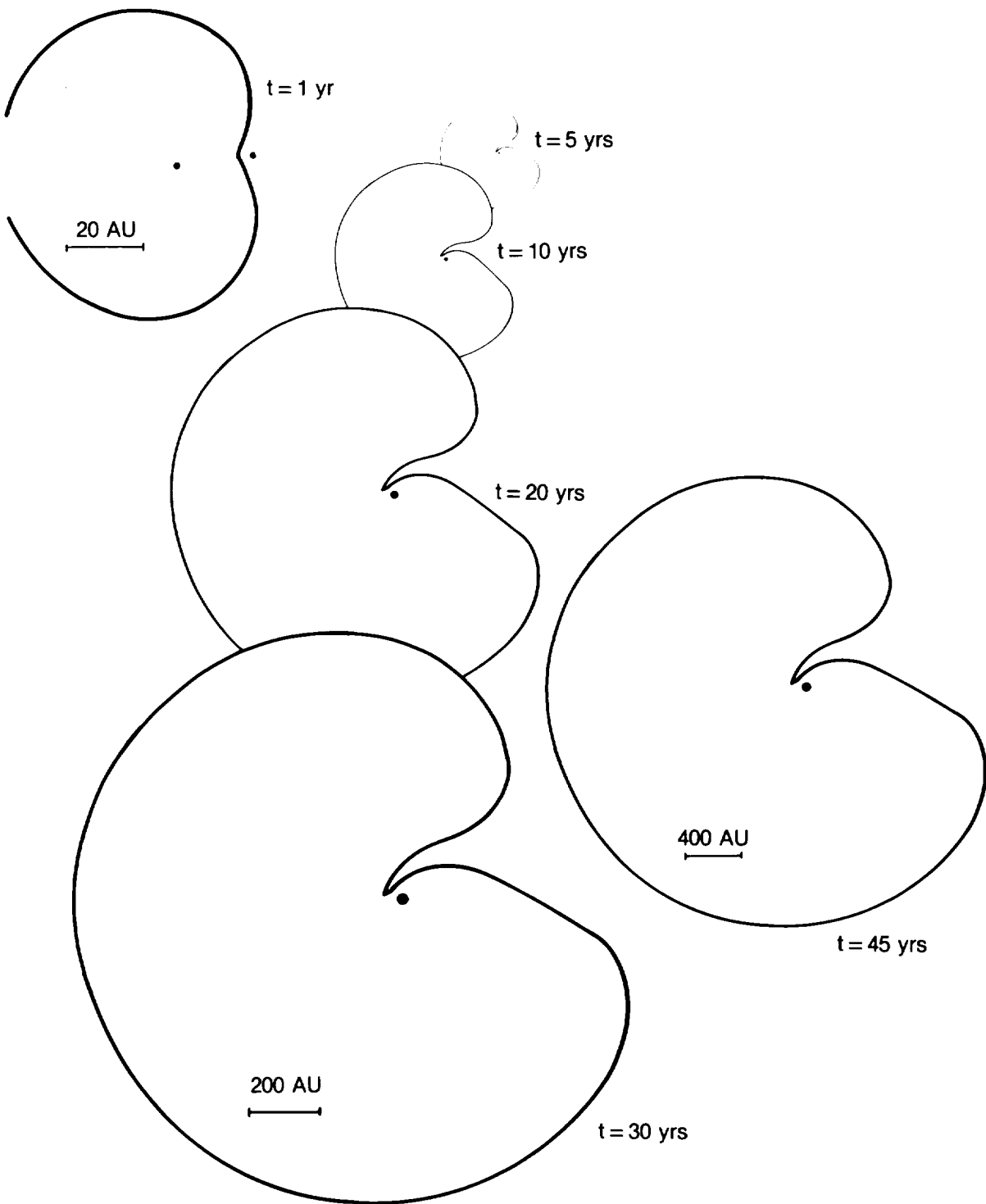


Figure 12-9. Evolution of colliding winds from Girard and Willson (1987).

rate of accretion change, but also thermonuclear flashes can occur.

All the binary models considered emphasize one physical process, and it is clear that several processes occur either simultaneously or at

least in different symbiotic stars. A realistic theory needs to consider, at the same time, all the processes mentioned. In addition, the physics of several of them is still not very well understood and needs further study before more definite conclusions can be drawn.